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THE DESIGN AND OPERATION OF THE FLUIDIZED BED COMBUSTOR DEVELOPED AT THE CANADIAN COMBUSTION RESEARCH LABORATORY

By E.J. Anthony, D.L. Desai and F.D. Friedrich

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ABSTRACT

Fluidized bed combustion (FBC) is an emerging technology which is generally viewed as having great promise for utilizing inferior fuels, such as low-grade coal, wood waste and municipal garbage. The emission of pollutants such as SO_2, NO_x and heavy metals is minimal.

Energy, Mines and Resources Canada is developing a broad program of full-scale demonstrations to establish the technical and economic viability of FBC technology in the commercial, industrial and utility sectors. While the demonstration program is intended to bring to commercial fruition the pilot-scale R & D carried out by many agencies over the past twenty years, it needs continued R & D support in a number of areas. These relate primarily to the performance in an FBC of specific fuels and sorbents under various conditions of bed temperature, excess air level, unit heat release rate, sorbent concentration and bed depth.

All the foregoing parameters can be studied in pilot-scale equipment, therefore in 1976 the Canadian Combustion Research Laboratory began the development of a 120 kW atmospheric fluidized bed combustor. A facility was developed which can, quickly and at modest cost, evaluate the performance of various fuels, and provide combustion performance and design information to support the full-scale demonstration program.

This report describes the construction and operation of the facility, and outlines the CCRL program of pilot-scale research.

LA CONCEPTION ET LA MISE EN OPÉRATION D'UN FOUR À COMBUSTION EN LIT FLUIDISÉ DÉVELOPPÉ AU LABORATOIRE CANDIEN DE RECHERCHE SUR LA COMBUSTION

par

E.J. Anthony, D.L. Desai et F.D. Friedrich

RÉSUMÉ

La combustion en lit fluidisé (CLF) représente une technologie nouvelle généralement perçue comme très prometteuse pour l'utilisation des carburants de qualité inférieure, comme les charbons de basse qualité, les résidus de bois et les déchêts municipaux. Les émanations polluantes comme le SO_2, le NO_x et les métaux lourds sont minimes.

Energie, Mines et Ressources Canada, est en train de développer un programme vaste et complet de démonstrations afin d'établir la viabilité de la technologie de la CLF dans les secteurs commerciaux, industriels et des services publics. Le programme de démonstration vise à faire porter fruit aux activités de R & D menées depuis les vingt dernières années par diverses agences; il a besoin d'un appui soutenu dans plusieurs domaines. Ces derniers se rapportent principalement à la performance du procédé de CLF en présence de combustibles et sorbants selon diverses conditions de température du lit, le niveau d'air en excès, le taux de dégagement de chaleur par unité, la concentration du sorbant et la profondeur du lit.

Tous les paramètres ci-haut peuvent être étudiés au moyen d'équipement à l'échelle pilote. Ainsi, en 1976, le Laboratoire Canadien de recherche sur la combustion a entrepris de développer un four à combustion en lit fluidisé à la pression atmosphérique de 120 kW. Une installation a été développée, permettant d'évaluer rapidement et économiquement la performance de divers carburants, la performance de combustion et d'offrir des renseignements sur la conception, afin d'appuyer le programme complet de demonstration.

Le présent rapport décrit la construction et la mise en opération de l'installation, et souligne les activités du programme du LCRC pour de la recherche à l'échelle pilote.

DESCRIPTION OF THE PILOT-SCALE FACILITY

The CCRL pilot-scale AFBC facility consists of four main components: the combustor, the fuel feed system, the freeboard and the gas clean-up system. These are shown schematically in Fig. 1 and are described in the following sections.

THE COMBUSTOR

The combustor consists of a stainless steel cylinder 1.19 m high having an inside diameter of 290 mm. As shown in Fig. 2, it is water cooled by means of a coaxial cylinder 380 mm ID which provides a 44 mm annular passage for the coolant. Building service water enters the bottom of the water jacket via a manual control valve and an integrating water meter, and discharges from the top of the combustor to drain.

In a small combustor, bare water-cooled walls present too great a heat sink for the bed to operate at the desired temperature, therefore the inner cylinder of the CCRL combustor is lined with refractory. A 20 mm layer of castable insulating refractory (Fiberfrax Variform B) protected from abrasion by an Inconel liner 4 mm thick was applied. This reduced the inside diameter of the combustor to about 240 mm, and made the combustor nearly adiabatic, permitting combustion trials with heat inputs as low as 30 kW. The combination of refractory insulation and Inconel liner served moderately well, and was used in a number of trials, but the repeated heating and cooling led to severe distortion of liner and eventual cracking of the refractory.

Additional cooling was provided by a water injection port situated 305 mm above the distributor plate. The water injection port was capable of delivering up to 100 kg/h of water. Typical values for water injection were in the range of 10 to 30 kg/h

The bed and freeboard were equipped with numerous ports for solids handling, probing and visual inspection. A complete list of these is provided in Table 1.

Additional thermocouples, connected via a 12 channel digital thermometer to a fluke data logger, were provided to the inlet and outlet of the water jacket. Water flow was controlled to prevent the outlet temperature from rising above 80°C. The pressure probes were connected to a manometer and the readings were logged manually.

The Propane - Air Preheat Burner

Before the test fuel was introduced into the combustor the bed material was preheated to temperatures above 500°C to facilitate fuel ignition on entry into the bed (Fig. 3).

The preheat burner screwed into a 127 x 76 mm ID nipple. This in turn was welded to a 150 x 89 mm ID preheat combustion chamber which was connected to a 76 mm port leading to the combustor at a height of 130 mm.

Part of the feed air was directed into the burner through a swirler 5 mm before the propane supply nozzle. Commercial grade propane (95% pure) was supplied via a 90.8 kg cylinder and flowmeter (rate up to 9.3 m^3/h).

Typical propane flow rates of 2.2 m^3/h were employed (this corresponds to heat input of 50 kW). At higher flow rates the propane froze in the cylinder. Fortunately higher flow rates were only necessary near the end of useful life of the Inconel liner.

The burner gases were ignited by a standard automobile "long tip" spark plug connected to an AC/DC transformer. As the burner operated against the back pressure of the bed, it was necessary to check the flame stability regularly through a small observation port 76 mm in front of the air swirler.

The burner assembly constructed from standard pipe fittings, was lined with wet pack refractory to provide thermal protection for the operators.

COMBUSTION AIR SUPPLY

The air used for the propane pre-heat burner, the combustion of coal and the coal pneumatic injection system was supplied by a centrifugal type blower manufactured by the Buffalo Forge Company. The blower was powered by a 11.2 kW electric motor and was capable of delivering 22.36m^3/s of air at 17.2 kPa static pressure, 21°C and 101 kPa barometric pressure.

All flow rates were monitored with a calibrated manometer connected across a 48.46 mm orifice plate (orifice plates of 8.63 and 62.28 mm were also used with this system) and controlled by gate valves.

A rotameter with a capacity of up to 54 m^3/h diverted part of the air flow to the coal feed line.

The Air Distributor and Windbox

The air distributor consisted of a 457 x 457 x 6 mm stainless steel

plate incorporating 36 stainless steel oil nozzles (Fig. 4). The hexagonal nozzles were 18 mm high with 1.8 mm hole drilled into each face.

The nozzles were located in concentric circles of 64, 130 and 190 mm diameters containing 6, 12 and 18 nozzles respectively. This arrangement gave even distribution of air and good fluidization. Typical fluidizing velocities ranged from 0.6 to 4 m/s.

A 25 mm hole in the center of the distributor plate allowed excess bed material to be withdrawn in a pipe through the windbox and a water cooled system to a cyclone separator connected to a vacuum pump. This arrangement allowed the bed material to be collected at the end of every run as well as permitting the bed height to be controlled (Fig. 2). The air distributor was bolted to a 305 x 305 x 203 mm metal windbox.

THE FUEL FEED SYSTEM

The fuel feed system is shown diagramatically in Fig. 5. There are two main components, a hopper and a feed monitoring system. The hopper consisted of a cylindrical mild steel container with a removable "seal tight" lid. The upper cylindrical section was 0.53 m in diameter and 0.86 m high. The bottom 0.43 m of the hopper, the conical section tapered from 0.53 m to 0.38 m. A 25 mm diameter PVC tube was connected to the air supply system to the top of the hopper to ensure that the positive pressure in the bed would not prevent the fuel from flowing.

The coal was crushed to 6 mm or less before being loaded through a funnel to a sealable 76 mm diameter port in the top of the hopper lid. Once in the hopper the coal passed through a 51 mm ball valve to a section of 76 mm diameter lucite tubing (which held approximately 0.23 kg of coal and allowed one to view the coal flow) and then fell onto a rotating plate 250 mm in diameter placed 50 mm below the column. The plate had a mechanical scrapper or rable arm situated 1 mm above it to dislodge coal, causing it to fall into the air injected into the bed. This allowed the fuel feed rate to be controlled by adjusting the speed of the rotation of the plate.

A gearbox controlled the speed of the plate which was recorded directly in rpm using a tachometer. This system dealt satisfactorily with coal up to 6 mm in size.

The feed rate was determined by recording the change in weight of the hopper which sat on a "Toledo weighing scale" by difference. The weigh scale, capable of reading up to 1 Mg with an accuracy of 0.2 kg, gave a completely satisfactory performance. The hopper capacity of over 160 kg of coal allowed 8 or more hours of continuous operation.

The feed system was not without difficulties. It was able to handle dry coal up to 6 mm in size but frequently jammed because the cylindrical limestone particles pass through a 6 mm sieve but depending on their orientation jam the feed line. This led to a modification in the hopper and feed system in the last two years of operation to enable it to handle fuel with a top size of up to 50 mm and higher surface moisture content (up to 7%).

The replacement system consists of a 0.6 x 0.46 x 1.5 m rectangular mild steel fuel hopper with two sides tapered for the lower 0.6 m, capable of holding approximately 310 kg of coal (Fig. 6).

The hopper was charged from the top. A bolt-on-lid secured the hopper to prevent blow back from the combustor. Two sides of the hopper sloped inwards to form a trough. At the bottom a screw feeder with a variable speed drive controlled the feed rate and discharged through a flexible connection to another variable speed water-cooled screw conveyor. The fuel was injected into the combustor through one of the two feed ports. The overhead feed port was located approximately 1.5 m above the distributor plate. The in-bed feed port was located approximately 0.3 m above the distributor plate.

The Freeboard and Exhaust System

The 1.8 m freeboard was mounted on top of the combustor. The bottom has a conical shape tapering from a 0.6 m ID to the 0.34 m ID of the combustor liner. The increase in the diameter from the combustor zone to the freeboard allowed a reduction in velocity of the combustion gases, thus creating more favourable conditions for settling of elutriated particles as well as allowing more time for burnout.

The entire outer shell of the freeboard was constructed of 5 mm stainless steel. The interior of the lower conical section was lined with a 25 mm thick layer of chrome ore refractory covered with a 3 mm Inconel shell. The exterior of the freeboard was insulated with 50 mm of fiberfrax blanket held in place by an aluminum covering.

The 1.73 m high modified freeboard used in later work was lined with insulating firebricks (51 mm thick). Its inside diameter was 502 mm for the upper 1.045 m of its length. Below that a 175 mm long conical section tapered from an internal diameter of 283 mm to the combustor diameter.

The top of the freeboard was connected via 150 mm, 4 m long flexible stainless steel pipe to the multicyclone.

The Multicyclone

The multicyclone was housed in a 1.98 m stainless steel vessel with cross-sectional dimensions of 760 by 305 mm. The top 460 mm housed the 3 cyclone units. Normally all but one of these units was blocked off to maintain cyclone pressure drop and hence collection efficiency. To prevent condensation in the cyclones this section was insulated and provided with heating rods.

The normal performance specification was 90% efficiency in collecting particles equal to or greater than 10 microns in size, at a pressure drop of 50 mm W.C. The entire assembly was insulated and was suitable for operation at about 600°C.

The flue gases then passed from the multicyclone to the stack through an old boiler used as a heat sink.

Instruments

Gas concentrations (CO, CO_2, O_2), fuel weight and temperatures were recorded every 5 minutes on a fluke 2240B data logger. The CO, CO_2 analyser were non dispersive IR instruments and the oxygen analyser was a paramagnetic type. For later work a chemiluminescent NO_x analyser and a non dispersive IR instrument for SO_2 were also used.

Measurement Techniques

a) Gas Sampling

The gases were first drawn off through a small cyclone separator, a cooling bath, a filter containing glass wool and finally a dri-rite package before going to the CO, CO_2, O_2, NO_x and SO_2 analysers via a flexible tube (Fig. 1).

During most of the operations of the Mark I, SO_x was determined chemically and not instrumentally. It was drawn from the top of the freeboard through a glass lined probe using a vacuum pump. The gas passed through a glass wool filter in the end of the probe to remove fly ash and particulate matter and then into an SO_3 trap. The trap consisting of a section of PVC tubing (6.4 mm ID) wrapped around a circular support, was submerged in a water bath. The gas sample passed through the section of PVC tubing to allow the temperature of the gas to reach that of the water bath. The bath temperature was kept at 74°C to condense the SO_3 in the form of sulphuric acid droplets while allowing little or no water condensation. This prevented the possibility of loss of SO_2 by solution in the water condensate.

The gas was then drawn through 1 or more bubblers containing sodium tetrachloromercurate (NaTCM) to fix the SO_2 in solution. The number of bubblers and the amount of NaTCM used was varied to ensure that SO_2 saturation did not occur.

The sampling pump was located downstream of the rest of the sampling equipment. This allowed the use of a bypass valve or the pump inlet to control the sampling rate without diluting the sample.

The SO_3 was determined by titration with $BaClO_4$ and the SO_2 by a modified West Gaeke Procedure (1,2). Experience demonstrated that the latter method was unsuitable for high concentrations of SO_2 (>1000 ppm in the flue gas) leading to considerable errors (20% or more). Thus this apparatus and procedure was replaced by an I.R. instrumental method of determining SO_2.

Solid Sampling

The dust loading system, sampling train and pump systems are shown in Fig. 7. Pitot tube measurements were used to adjust the sampling rates such that the velocity of the sampling gas entering the probe was equal to the velocity of the flue gas (isokinetic sampling). Samples were drawn from the multicyclone outlet.

Sample flow was regulated using a gate valve and a rotameter having 1.7 m^3/h capacity at 100 per cent flow. Before the gas passed through the pumping system the moisture was condensed in a "Blue M cooling bath".

The dust sample passed through the cyclone separator consisting of a outer cup and a central cone containing screens. Dust collected in the cup was plus 25 microns and on the screens 25 x 1 micron.

Submicron particles travelled on to the Radar filter paper holder containing the Schleicher and Schuwell 25 standard glass fibre collection filter. Both the cyclone and the Radar filter paper holder were heated by electric resistance heaters to prevent condensation of water vapour.

Solid samples from both the bed and the cyclone were collected and subjected to chemical analysis. The total weight of the cyclone deposit was recorded at the end of each test.

The Fluidized Bed Pretest Procedure

A sample of the coal was taken and an ultimate and proximate analysis was obtained. The calorific value of the coal was also determined.

The sand used as the bed material was dried if it was wet, to enable initial fluidization and its size distribution was determined by Tyler sieve analysis.

When the pneumatic feed system was used the coal was examined to see whether it was dry enough to feed without giving rise to compaction and fuel blockage in the feed system. A simple test was used to determine whether the coal was dry enough; if a sample did not stay compacted after being compressed with a firm hand grip it was considered sufficiently dry.

If the coal was too wet it was first dried before crushing to a 6 mm size and then its particle size distribution was determined. In latter experiments with the 'screw feed' system the coal was sieved and only the fraction over 50 mm was crushed.

The coal was loaded into a hopper from barrels through a 6 mm screen to ensure that no stones or large coal particles escaped crushing. When limestone was used in the tests it was also dried and crushed to -6 mm and then premixed with the coal to give the desired Ca/S ratio before being charged in the coal hopper.

Before commencing operation 26 kg of sand was charged in the combustor through a 76 mm nipple in the top of the freeboard.

Samples of the fuel were also taken, just prior to and just after each test to determine their moisture content.

The analysers were switched on several hours before a test series began and then left on during a series of tests. This ensure thermal stability and prevented delays due to the long warm up periods required by these instruments. Prior to each test the CO_2, CO, O_2, NO_x and SO_2 analysers were spanned and zeroed and all filters, lines and pumps were checked.

The fluke data logger was programmed to tabulate data every 5 minutes. Occasionally the pressure ports of the combustor became blocked with bed material and these were blown clear with a blast of compressed air. The level of the fluid on the manometers were also zeroed prior to the test.

Start up procedure

The air blower was switched on and allowed to reach its maximum pressure while keeping the valve to the bed shut. Positive pressure was then set on the air lines to the bed, coal feed and propane air burner. This procedure prevented them becoming blocked on fluidization of the bed. Any blockages discovered were cleared before proceeding.

A quick blast of air through the distributor plate reduced the initial resistance to fluidization.

The regulating valve on the air-line to the bed was opened and the air flow rate increased to a precalculated value required to fluidize the bed. In some cases it was also found necessary to supply a large amount of air through the preheat burner to clear sand from the burner port. The manometers monitoring the pressure drop across 200 mm at the bed (situated at 102 and 305 mm above the distributer plate) provided a visual assurance of fluidization since the pressure drop first increased linearly as the valve to the air line was opened and then proceeded to fall and finally to rapidly fluctuate around a fixed point.

The induced draft system was then adjusted to provide approximately 3.6 mm (H_2O) vacuum at the cyclone outlet. The cooling water for the combustor and the air flow rate to the burner were adjusted to preset rates. The propane was introduced to the burner at a pressure of 35 kPa and ignited with a spark ignition system. The burner and flame were checked periodically via the inspection port and the flow rate adjusted if necessary.

The temperatures in the bed at the 102 mm and 300 mm levels were monitored to ensure that complete fluidization and good heat transfer to all parts of the bed was occuring. As the temperature of the bed increased the

amount of air for fluidization was decreased to increase the heating rate of the bed.

The coal was introduced when the bed reached a preset temperature (normally 650°C). When the temperature in the bed began to rise rapidly, indicating that the coal was undergoing self sustaining combustion, the propane supply was shut off and then the air supply to the burner closed down. The fuel feed rate was then adjusted to the desired value and the air flow was adjusted to give a pre-determined excess oxygen concentration in the flue gas. As equilibrum in the bed was achieved, the water injection into the bed was adjusted to maintain the target bed temperature. The flow rate of water in the cooling jacket was always maintained to ensure that the outlet temperature was less then 80°C and to ensure that boiling did not occur in the water jacket.

The Test Procedure

The test was run for a pre-determined period of time (typically from 2 to 8 hours). The temperatures, pressures, air flow rates, feed rate and gas concentrations were recorded every five minutes; air flow rates and water flow rates and pressures being logged manually. In addition SO_2 and SO_3 concentrations were determined 3 times during the run for all the tests which employed chemical methods of measuring SO_2. Later the IR SO_2 analyser was used and data was logged by the fluke data logger. NO and NO_x concentrations were also recorded from 3 to 5 times during each test. In some of the initial tests only the temperatures were logged electronically and all the analyses, feed rates and pressures were logged manually as well.

During every run at least 3 dust loadings were taken. Such measurements normally took 15 minutes to complete and required a sample (0.13 m^3) of the gas to be drawn off. During sampling the "small cyclone" separator outlet temperature was also recorded.

If necessary, bed-material was drawn off during a run to maintain a constant bed height. Samples of bed material were taken during a test and analyzed chemically.

Post Test Procedure

When all the test samples and data had been obtained and the test run for the desired length of time at the 'steady state' condition completed, the

fuel feed and then the injection water flow, if any, were stopped. The flow rate of cooling water to the jacket was then increased to hasten cooling until the bed reached 200°C.

The fluidizing air was left on until the bed temperature was reduced to 200°C. The bed material was then removed through the center of the distributor into a small cyclone using a portable industrial vacuum cleaner to provide the suction before the fluidizing air was switched off.

The bed material was weighed, thoroughly mixed and a representative sample taken for particle size distribution, per cent combustibles and total sulphur analysis. The total cyclone deposit was also removed, weighed and subject to the same analysis as the bed material.

CONCLUSIONS

The structure and operation of a pilot scale 240 mm diameter, 120 kw AFBC at the Combustion and Carbonization Research Laboratories which was operated from 1976 to 1980 has been described in detail. During its period of operation it was successfully used to examine the combustion characteristic of 6 Canadian fuels including eastern and western Canadian coals and one petroleum coke (3-7). This unit had a number of deficiencies and was subsequently replaced by a larger more versatile (380 x 400 mm) AFBC (8).

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Table 1 - Solid handling and probing port location

Purpose of the Port	Height above the distributor plate (mm)	Additional information
Visual inspection ports (38 mm diameter)	610°, 910° and 4000	° These were equipped with pneumatic injection nozzles to remove elutriated bed material during operation
Ports for pressure probes (76 mm diameter)	100° and 305	These were situated in the active bed zone. (Typical bed height on fluidization was 460 mm)
Ports for thermocouples (76 mm diameter)	305, 610, 910, 1500 and 400	All thermocouples employed in this system were steel jacketed chromel alumel thermocouples
Water injection port (40 mm diameter)	305	This was connected to a rotameter capable of delivering 100 kg/h of water

Table 1 - (Cont'd)

Purpose of the Port	Height above the distributor plate (mm)	Additional information
Feed Port (76 mm diameter)	100*, 1500	The 1500 mm feed port was a later addition to the equipment to permit overbed feed and necessitated a change of feed system from pneumatic to screw feed
Port for preheat burner (76 mm diameter)	130	
Solid removal (25 mm diameter)	0	This was located in the center of the distributor plate
Port for addition of bed solids	4000	This doubled as a visual inspection port during shutdown to allow inspection of the liner

* The feed port served as an entry for both a pressure probe and a thermocouple. The thermocouple projected 15 mm beyond the feed port to ensure it was not chilled by transport air.

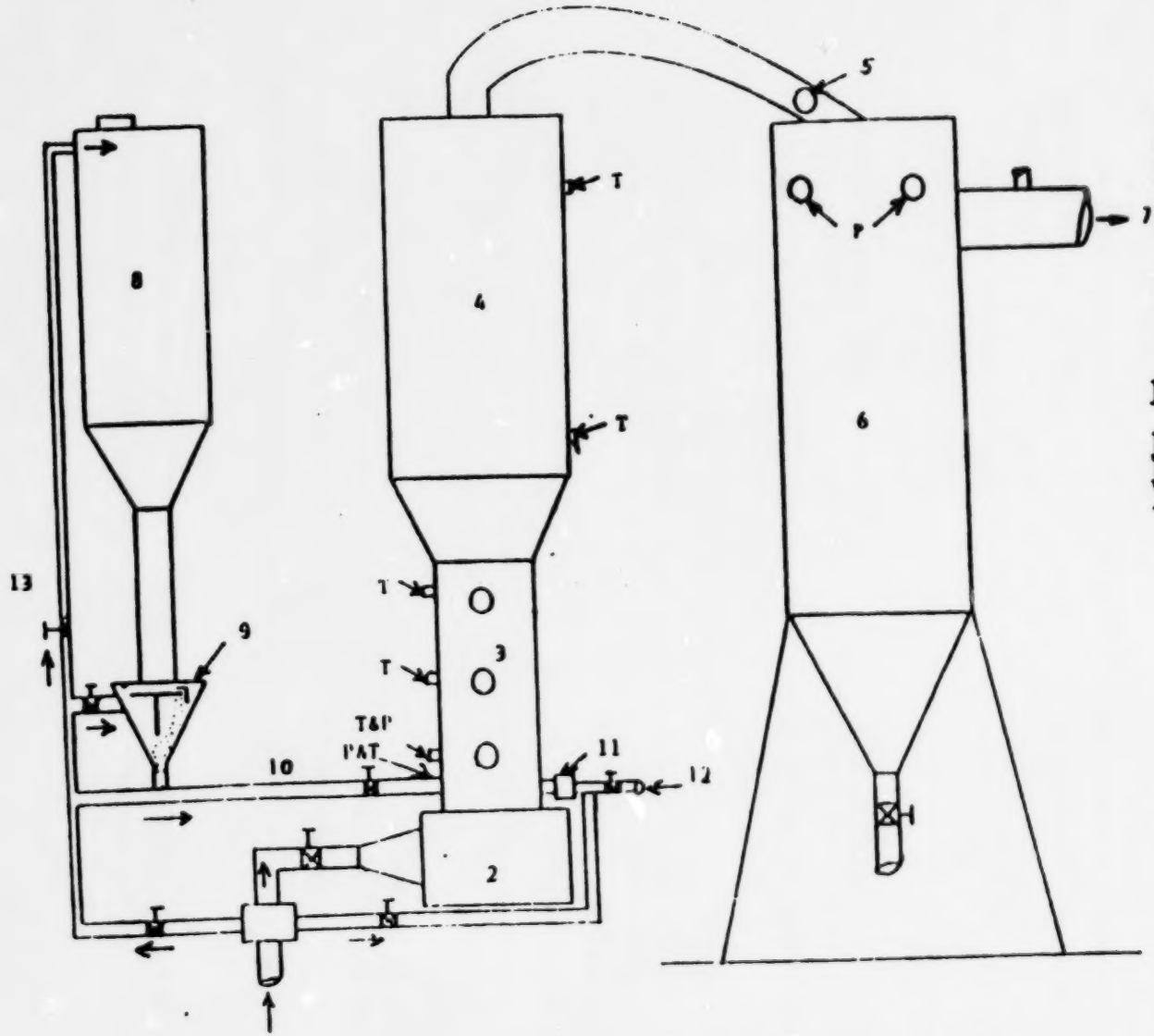

Fig. 1 Schematic of the fluid combustor and ancillary equippment

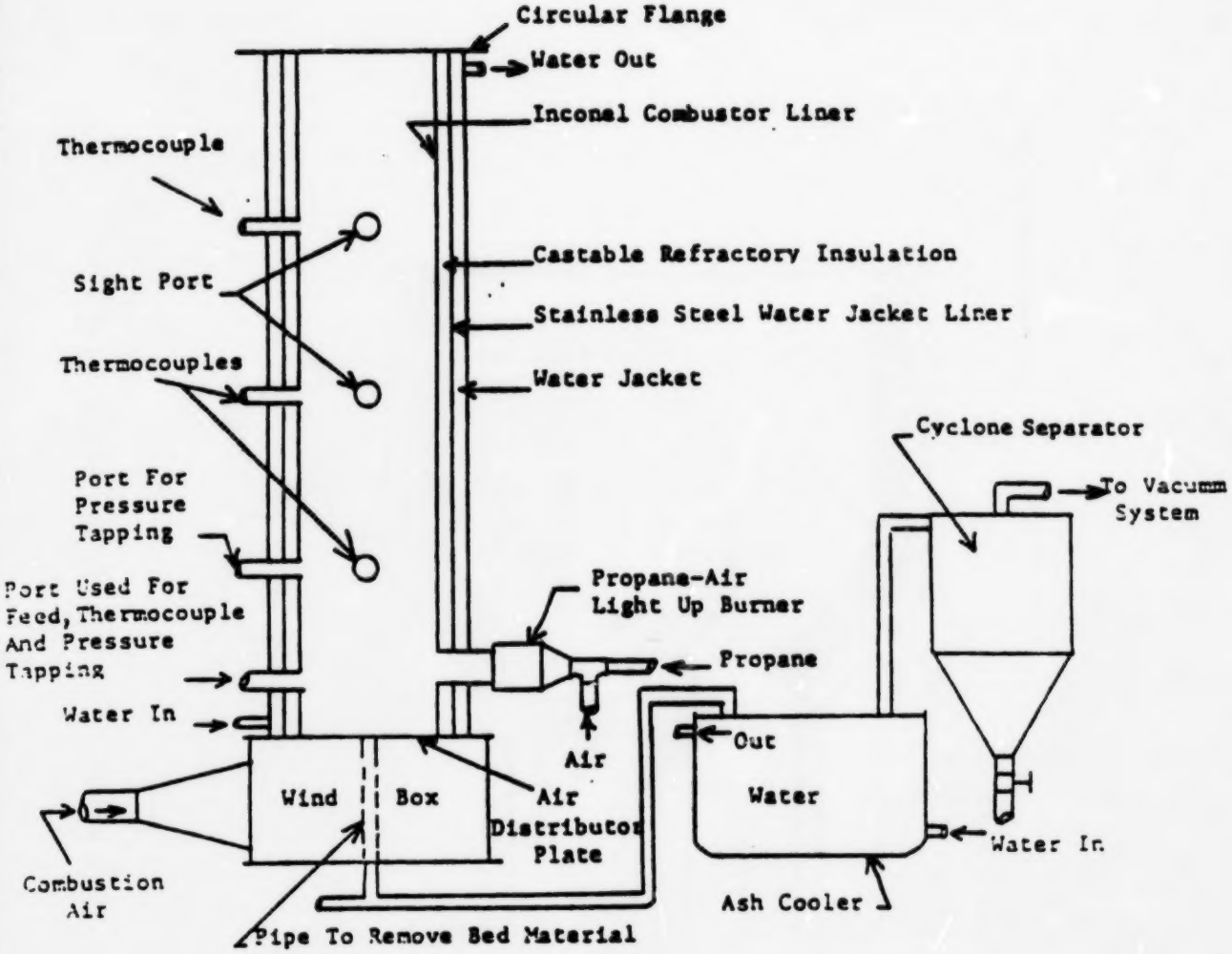

FIGURE 2 - A SCHEMATIC SECTION OF THE CCRL AFBC SHOWING THE COMBUSTOR AND BED REMOVAL SYSTEM.

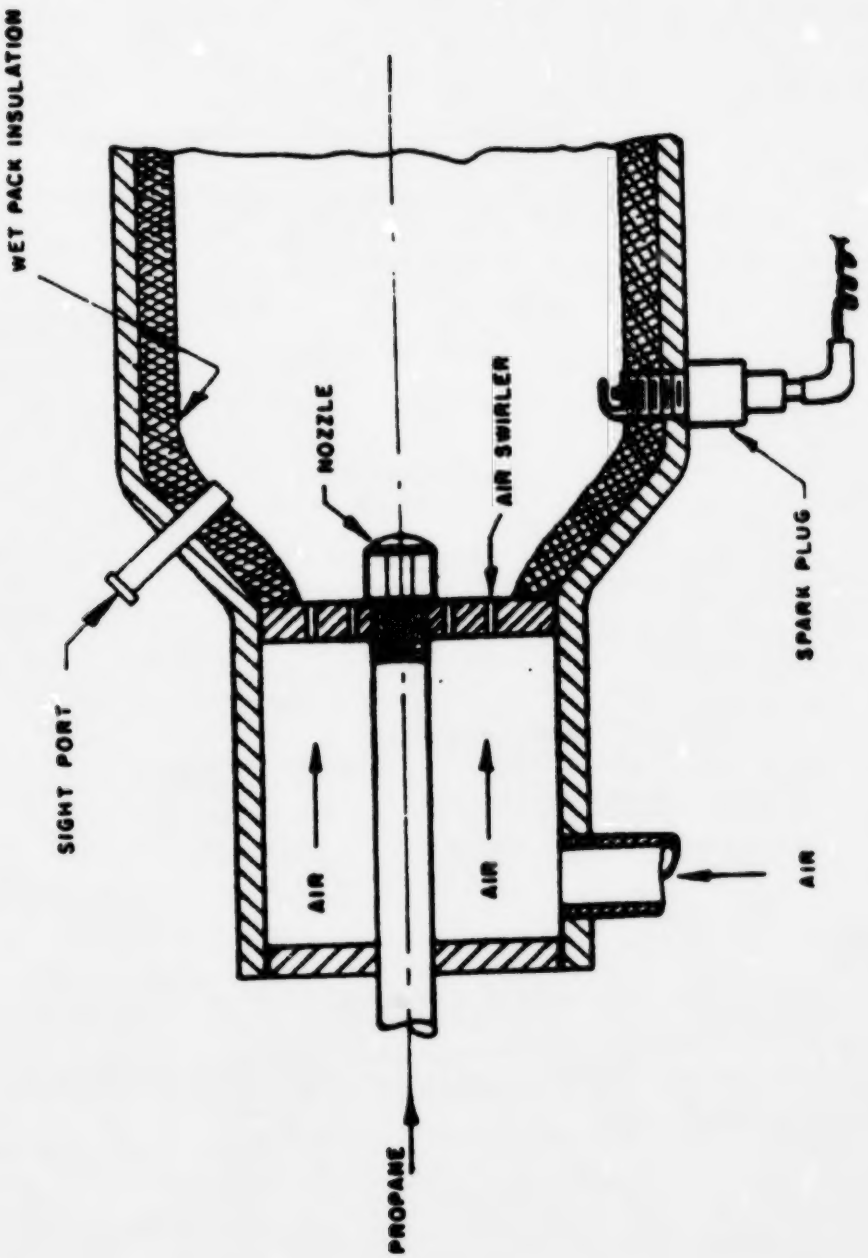

FIGURE 3 - THE LIGHT-UP BURNER FOR THE PILOT-SCALE AFBC

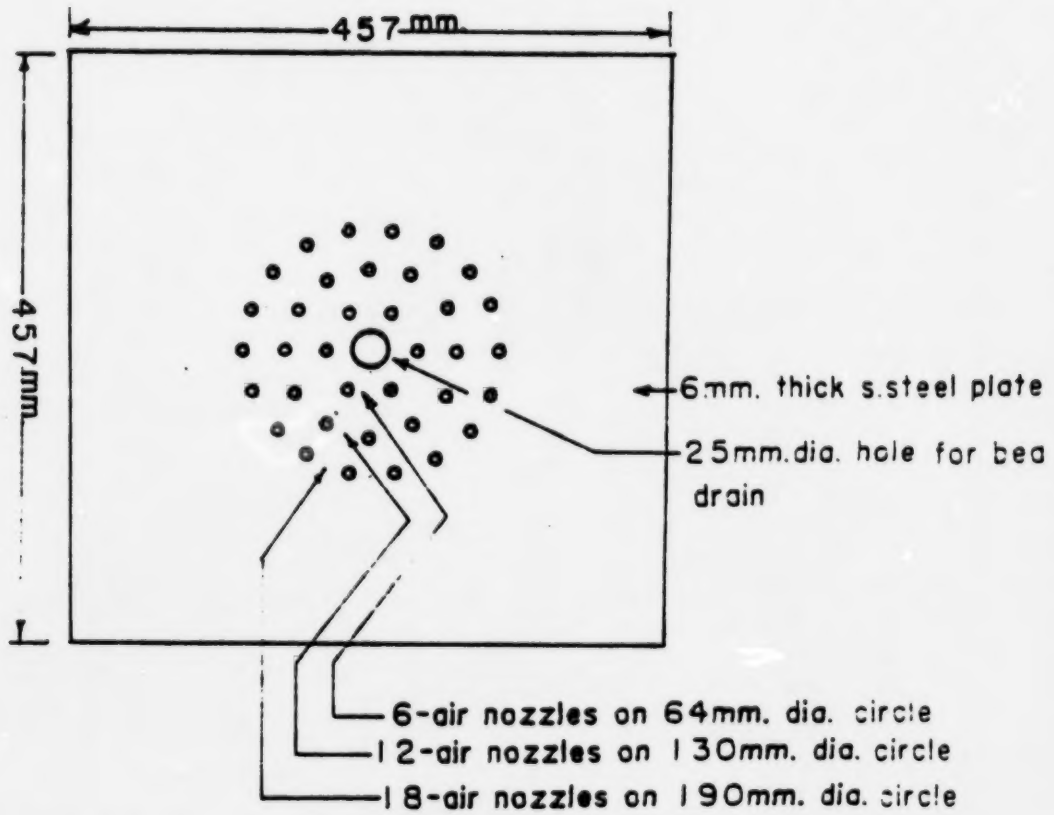
457 mm.
457 mm.
6 mm. thick s.steel plate
25 mm. dia. hole for bed drain
6-air nozzles on 64 mm. dia. circle
12-air nozzles on 130 mm. dia. circle
18-air nozzles on 190 mm. dia. circle

FIG.3 SCHEMATIC OF AIR DISTRIBUTOR PLATE

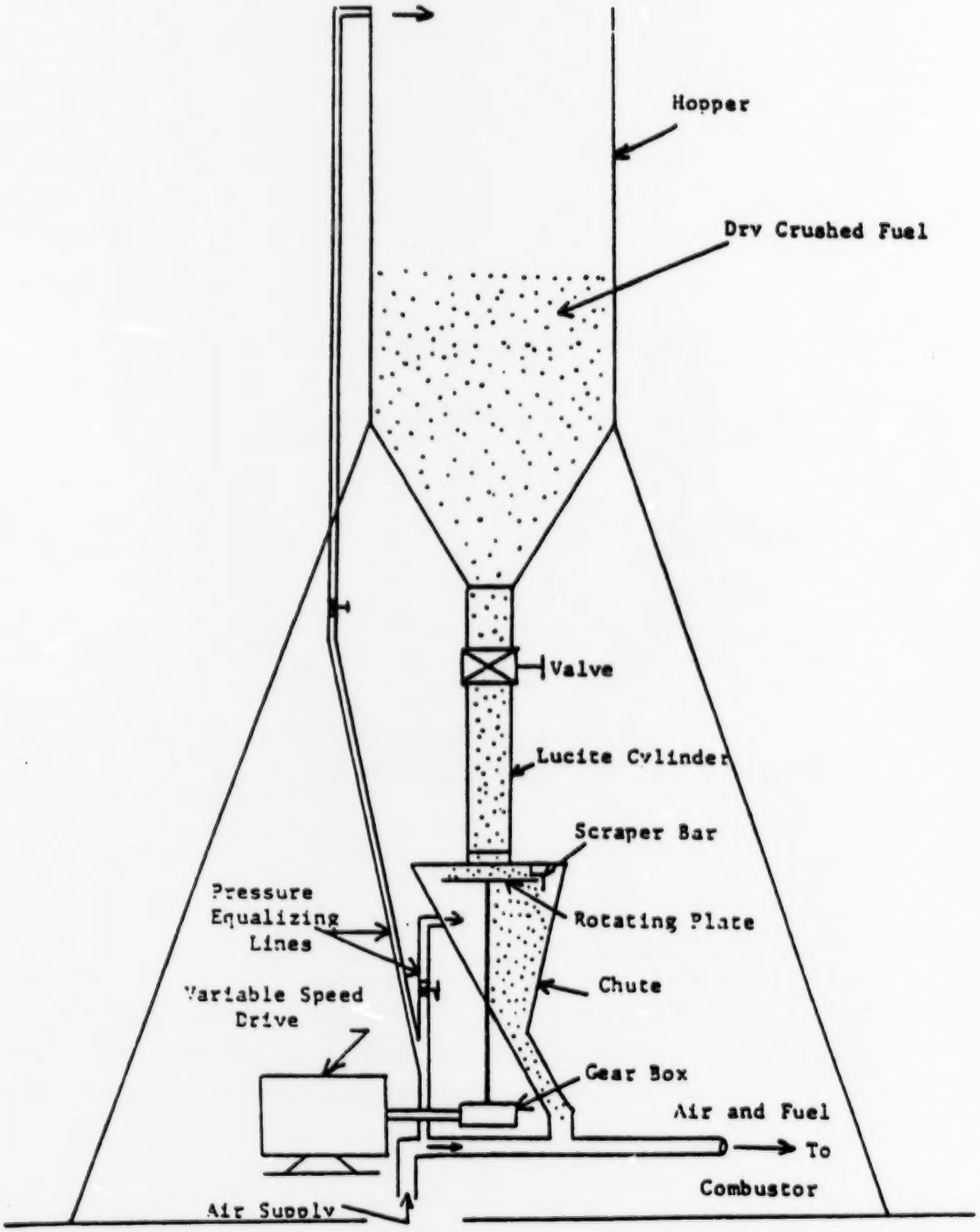

FIGURE 5 - A SCHEMATIC OF THE COAL HOPPER AND FEED SYSTEM

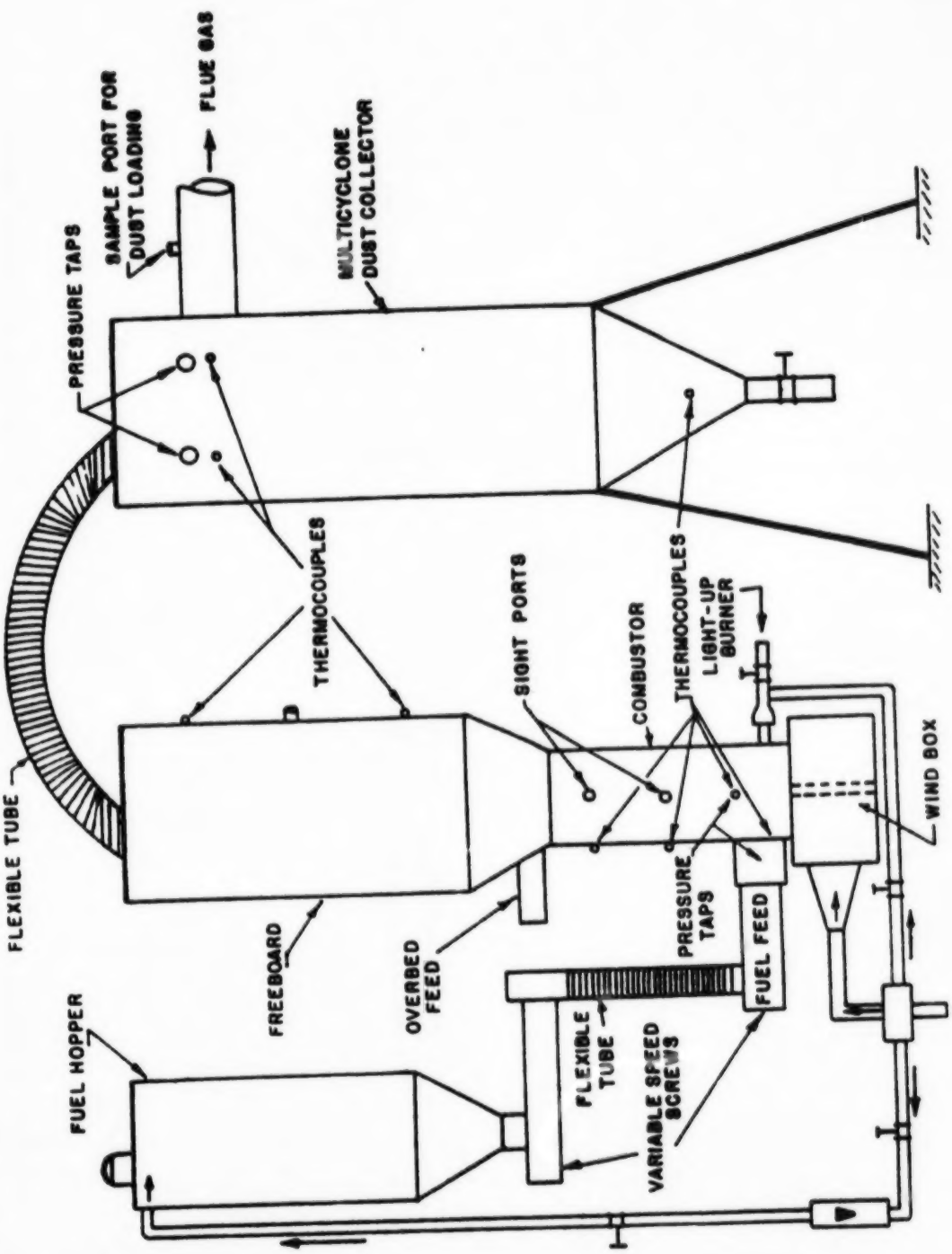

FIGURE 6 - SCHEMATIC OF PILOT-SCALE ATMOSPHERIC FLUIDIZED-BED COMBUSTOR.

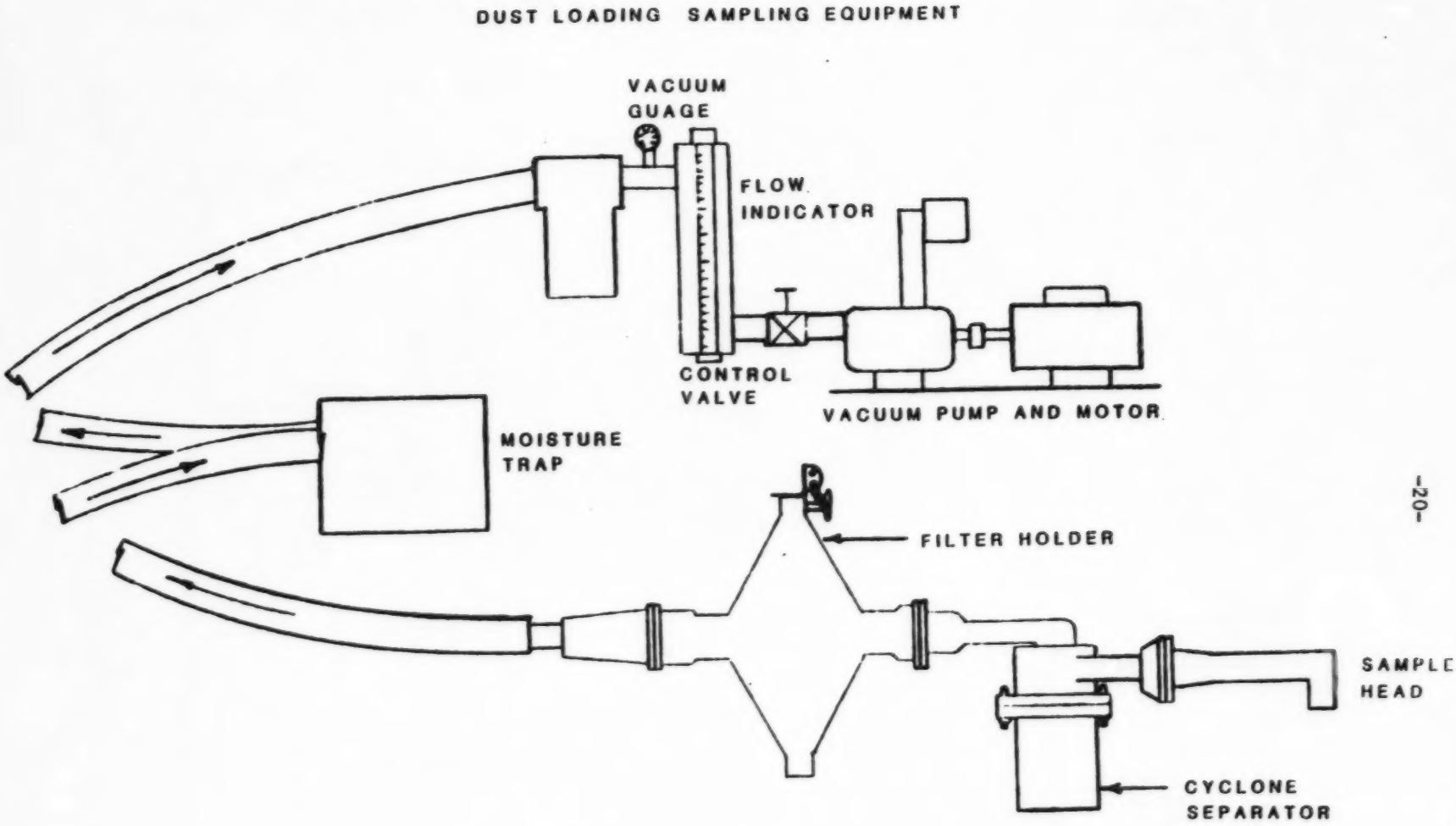

FIGURE 7 -THE DUST LOADING & SAMPLING EQUIPMENT